AD-A022 994

THE USE OF ELECTROCORTICAL ACTIVITY TO MONITOR HUMAN DECISION MAKING

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Prepared for:

Defense Advanced Research Projects Agency

March 1976

University of Illinois at Urbana-Champaign

Department of Psychology

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Final Technical Report

Period Terminating June 29, 1975

Contract Details:

Contract Number:	*DAHC 15 73 C 0318*
ARPA Order Number:	*2410*
Program Code Number:	*3D20*
Date of Contract:	*29 June 1973*
Expiration Date:	*29 June 1975*
Amount of Contract:	*$457,334*

Contractor Details:

Name of Contractor: The Board of Trustees of the University of Illinois at Urbana-Champaign
Principal Investigator:
Dr. Emanuel Donchin
Phone: (217) 333-3384

Signature: E. Donchin
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Professor

43

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: DAHC 15 73 C 0318	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): THE USE OF ELECTROCORTICAL ACTIVITY TO MONITOR HUMAN DECISION MAKING	5. TYPE OF REPORT & PERIOD COVERED: Final Technical Report June 1973 - June 1975
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): Emanuel Donchin	8. CONTRACT OR GRANT NUMBER(s): DAHC 15 73 C 0318
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Emanuel Donchin, Department of Psychology, University of Illinois, Champaign, IL 61820	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 1001/193
11. CONTROLLING OFFICE NAME AND ADDRESS: Defense Advanced Research Projects Agency, 1400 Wilson Boulevard, Arlington, Virginia 22209	12. REPORT DATE: March 1976
	13. NUMBER OF PAGES: 39
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): ONR Resident Representative, University of Illinois, Room 110, 55 E. Armory St. Champaign, IL 61820	15. SECURITY CLASS. (of this report): DO A7
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Unclassified. Approved for Public Release. Distribution Unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Biocybernetics, Psychophysiology, Evoked Responses, Brain Potentials, EEG, Human-Performance, Aircraft Control, Computer Assisted Instruction, CNV, P300.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Work in this, and in other laboratories, demonstrated that cognitive events can be inferred from cortical potentials which can be recorded through the scalp of intact, awake human subjects. Specific components of these event related potentials (ERPs) have been shown to be manifestations of such cognitive events as the preparation to perform a response, the preparation to intake and process information, the registration of a

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

surprising event, or the processing of task relevant information. We have developed the use of Principal Component Analysis for the dissociation of the ERP components. Using this technique we have been able to greatly refine the resolution with which we can dissect the ERP into cognitively relevant components. At the same time we have shown that Stepwise Discriminant Analysis can be used to detect and identify the brain responses without requiring the averaging of multiple responses.

It has become quite evident that a useful lexicon of evoked response components exists and that "signal trial analysis techniques" can be developed. It appeared advisable therefore to terminate this three year project at the end of its second year and to initiate a five year project which would include as a major component the development and testing of practical applications of biocybernetic communication channels. A description of the new plan is included in this report. An annotated bibliography of all reports developed under this contract follows.

A

INTRODUCTION

The present document constitutes the Final Report on the effort conducted in this laboratory under contract #DAHC-15-73-C-0318 between July 1, 1973 and June 30, 1975. We originally contracted to perform during a three year period a series of investigations intended to assess the feasibility of using electrocortical activity to monitor human decision making within the context of ARPAs Biocybernetic Program. The prime intent of the project was to determine the extent to which a lexicon of evoked brain response components can be developed. Such a lexicon should allow strong inferences about decision making activities by the human operator to be based on electrocortical recordings. We were also to develop procedures for detecting and identifying the brain responses by techniques which do not require the averaging of multiple signals. These "single trial" techniques were deemed crucial for any future applications of the evoked response vocabulary in enhancing the performance of man-machine systems.

During the second year of the project it became quite evident that a useful lexicon of evoked response components exists and that "signal trial analysis techniques" can be developed. In particular the stepwise discriminant analysis approach we have been evaluating provide a promising tool in the development of real-life applications of biocybernetic communication channels. It appeared advisable, therefore, to propose the termination of this three year project at the end of its second year and to initiate a five year project which would include as a major component the development and testing of practical applications of biocybernetic communication channels. A proposal to this effect was submitted to ARPA on April 4 1975 and has been approved. Thus on July 1, 1975 this contract has been terminated and

the work in the laboratory is now continuing under contract #US NAVY N-000-14-76-C-0002 monitored by the Office of Naval Research. As the project has not in fact been terminated and the work is continuing albeit under a new organizational arrangement an effective way to report and summarize the achievements of the past two years is to present the bulk of the material included in the proposal which summarized the original project and outlined the plans for the continuation of the effort. This document consists of material included in the Research Proposal entitled "The Vocabulary of Brain Potentials: Inferring Cognitive Events from Brain Potentials in Operational Settings," submitted to ARPA by the University of Illinois on April 4, 1975. We have excluded passages pertaining to the management and budget of the continuing operation. This report also includes a detailed, annotated, bibliography of reports on work supported by this contract and published in the scientific literature. Material is thus available for several classes of readers. Those interested in a summary of the effort will find it in the initial, narrative, section. Those interested in a detailed review of our procedures and findings can find this through the annotated bibliography, and finally, a detailed summary of our projected experimental plans are presented in the final sections of the report.

NARRATIVE SUMMARY

1. Rationale

We have demonstrated that cognitive events can be inferred from cortical potentials which can be recorded through the scalp of intact, awake human subjects. Specific components of these event related potentials (ERPs) have been shown to be manifestations of such cognitive events as the preparation to perform a response, the preparation to intake and process information, the registration of a surprising event, or the processing of task relevant information.[(1)] With the application of powerful analytical techniques,[(2)] we have in the past few months been able to greatly refine the resolution with which we can dissect the ERP into cognitively relevant components.[(3)] We will refer to this phase of the work as the determination of the ERP vocabulary.

A brief summary of the available data on ERP component which are demonstrably associated with cognitive events follows.

An ERP is a transient series of voltage fluctuations induced in cortical tissue immediately following the occurrence of some critical inducing event. The ERPs can be induced by a variety of events such as the presentation of a stimulus, the occurrence of a response, a change in the rate of stimulation, etc. The amplitude of the response, as recorded from the scalp, is minute relative to the on-going brain wave activity (EEG), and it is only through the use of signal-averaging techniques that the waveform and characteristics of ERPs can be studied.

An ERP consists of a series of positive and negative peaks which continue for about 500 msec. The waveform, i.e., the sequence and timing of positive and negative peaks, depends on the eliciting event, on the state of the subject, and on the placement of the recording electrodes on the scalp. For any given set of conditions ERPs are quite consistent between individuals, yet

each individual tends to display a characteristic wave pattern. In the few published reports of ERPs recorded from the same individual over long periods the wave patterns proved remarkably stable.

Each peak-to-trough, or base-to-peak deflection appearing in the ERP at a consistent temporal interval following the eliciting event is called a "component." Many components are "exogenous," that is they represent the response of cortical tissue to the arrival of sensory volleys as a result of the activation of a peripheral sense organ. The exogenous components are often followed by what we shall call endogenous components. These represent cortical information processing invoked by the psychological demands of the context in which a stimulus is presented rather than by the physical properties of the stimulus. For example, we, and others, have shown that if a stimulus provides task-relevant information to a subject the ERP elicited by that stimulus will be characterized by a large positive going wave with a latency to the peak of about 300 msec. We call this component P300.

With few exceptions, ERP components are labeled by a <character><number> designation. The character indicates the polarity of the component (P = positive, N = negative), the number refers to the modal delay between the eliciting event and the peak of the component.

1. N100. Present in ERPs elicited by all stimuli of moderate and high intensities. Recent evidence suggests that the amplitude of N100 is a function of the degree to which subject is attending selectively to the modality in which the stimuli are presented.

2. N190. This ERP component, studied in detail in our laboratory, seems to be elicited whenever a rare, or unexpected, event occurs. It is of particular interest because it can be elicited by stimuli which are in fact in the periphery of the subject's attention span. Due to the fairly recent discovery of N190 the details of its relationship

to psychological variables have yet to be worked out.

3. *P300. This is the most robust of the endogenous ERP components. In more than a decade of research it has been recorded in many laboratories, in a large number of situations. It seems to be most reliably recorded in association with task-relevant, rare stimuli and seems to reflect in amplitude the complexity of the information processing invoked by the stimulus.*

4. *"Slow Wave". We have established that the P300 component is often followed by a slow potential shift which is affected by the same variables which are known to affect the P300 except that it has a different scalp distribution. Whereas P300 appears largely as a positive going potential peaking on the parietal (posterior) scalp, the slow wave is positive going on parietal electrodes and negative going in frontal electrodes.*

5. *The Contingent Negative Variation (The CNV). This wave precedes anticipated events in response to which the subject will have to perform a demanding motor, or mental, act. It is very reliably recorded during the warning interval (foreperiod) in a reaction time task, in the form of a negative ramp beginning about 400 msec after the warning stimulus and peaking just prior to the response-commanding (imperative) stimulus.*

6. *"Readiness Potential" (RP). This is a CNV-like wave. It is distinct only in the sense that it appears prior to self-paced voluntary responses. Its occurrence is independent of the presence of an eliciting, or a command stimulus. The relationship between the RP and the CNV is a subject of much active research and some controversy.*

The determination of the ERP vocabulary consists of defining with ever increasing resolution the specific psychological variables which determine

the amplitude and scalp distribution of these potentials. It is also necessary to develop techniques for dissecting any given waveform into its constituent components. These have been the main charges of our past research and we feel we made substantial progress. Specifically, we have developed a powerful combination of Principal Component analysis and analysis of variance which has enabled us to clarify the relationship between ERP components.[4]

As the known vocabulary of ERPs develops it becomes increasingly likely that the ERP might play an important role in man-computer interactions. If the vocabulary can be "understood" by a computer, and there is no doubt that it can, then an important communication link can be established between the operator and his equipment. At least three advantages are apparent in such a communication channel.

1. As the ERPs seem to, at least in part, manifest events in the non-verbalized substrate of cognition they may provide information which cannot be otherwise communicated by the operator.
2. The immediate access ERP components provide into the subject's cognitive world suggest that they might enhance communication speed.
3. The strong presumptive evidence that an individual's ERP is unique suggests that these potentials might constitute an ongoing self authenticating component of the communication process.

The project plan proposed here capitalizes on the success of the first two years of our ARPA support and is designed to develop realistic implementations of biocybernetic communication systems in simulated operational environments.

We see the following specific tasks.

a. Refine our present knowledge of the ERP vocabulary. Particular emphasis will be placed on the newly discovered N190 and "slow wave"

components, as well as on consolidating our understanding of P300 as a measure of the feedback subjects derive from specific stimuli.

b. Test the utility of the well established vocabulary in enhancing performance of operators controlling complex devices (with our major model being the aircraft cockpit).

c. Test the utility of the vocabulary in the Computer Assisted Instruction environment. Here the model will be the PLATO lesson and our goal the facilitation of interaction between the student and the teaching console.

The major difficulty in developing the ERP as a communication channel is the very low signal to noise ratio in the channel.[5] The ERPs are minute in amplitude relative to the "polyneural roar" of the ongoing EEG activity. In determining the vocabulary, signal to noise ratios can be enhanced through the use of signal-averaging. This technique relies, of course, on the repeated occurrence of the cognitive events as well as on the computer's precise knowledge of their time of occurrence. While this procedure is adequate for vocabulary identification it will not do for practical communication in operational environments. In these we must be able to identify the occurrence of ERP components in the ongoing EEG activity immediately following single occurrences of the specific events. The problem then becomes one of developing single-trial signal extraction techniques (STSE).

We have been developing STSE procedures for some time.[6] Work conducted with our present ARPA support indicates that Stepwise Discriminant Analysis (SWDA) procedures allow correct classification of trials at a hit rate of 80 percent. This hit rate is based on a crude application of SWDA. It is likely that STSE could be greatly improved by combining data from multiple channels and by prefiltering the ongoing EEG activity to eliminate energy in the "noise" bandwidth before discrimination begins. Development work on STSE

could not begin in earnest prior to the identification of the vocabulary and it is contingent on computational power which will be at our disposal according to present project plans. We intend to devote much effort to the single-trial problem. The development of a STSE is contingent also on the development of refined techniques to increase signal to noise ratio in the real-time evaluation of performance. In fact, failures to "correctly" detect ERPs on single trials may often be due to variability in the concomitant performance variables as much as it is due to inherent "noise" in the EEG. Thus the development of STSE techniques requires a conjoint measurement of performance and EEG variables. We need techniques which lead towards sufficiently accurate definitions and measures of single "performance" events, which can then be correlated with their ERP counterparts. The investigation of this problem and the development of such techniques will be directed by the Aviation Research Laboratory. Both research programs will be joined in an effort to improve the real-time evaluation of cognitive and behavioral events. All data collected in all experiments to be conducted in the laboratory would provide a data base for the development of STSE procedures. The operational environments in turn will be used for specific demonstrations of these procedures as they emerge.

2. Research Plan

Three concurrent activity streams will be maintained during the next year.

a. The procurement and installation of hardware and software for recording ERPs in simulated cockpits and in a CAI installation.

b. Intensive development of STSE techniques and the implementation of at least one demonstration in which a STSE is used in biocybernetic communication.

c. Continuation of work on vocabulary identification, using our

existing facility.

It should be emphasized that even though a major development effort will be required by activity stream a we plan to maintain a steady level of effort in the other two categories. If the proposed personnel contingent is approved the installation of the new laboratory can be accomplished with no reduction in our present rate or progress. Moreover, we intend to support the use of our facilities by remote investigators as the need arises.

We shall now describe briefly specific aims and goals of the three activity streams.

2.1 The development of a Performance lab.

The present project will be conducted in close collaboration with the Aviation Research Laboratory at the University of Illinois (ARL). The rapid development in aircraft technology during recent years has increased the emphasis on the assessment of human capacity with regard to attention capabilities and information processing. The emerging cockpit typically requires man to be an information manager or fast decision maker rather than a direct controller of flight variables. In the past several years the ARL has conducted a comprehensive program directed among other things at the development of general rules and prediction equations for the evaluation of task load and operator efficiency. In particular this research has developed a new methodological approach for measuring operator load, as well as individual differences in attention capabilities. The method incorporates adaptive techniques, sensitive feedback devices and on line evaluation of operator performance.

We intend to construct in collaboration with ARL a laboratory which would allow recording of ERP in an environment in which the performance evaluation methodology is implemented. This will require, in addition to our standard computer-based electrophysiological data acquisition system, arrangements for presenting audio-visual displays of considerable complexity while subjects

manipulate control gear. The computer supporting this facility should be capable of generating on-line, and in real time, tasks of realistic complexity.

By the end of the first year of the project we will accomplish the following:

a. Design, procure and install the laboratory facility described above.

b. Develop procedures for routine recording of EEG, and ERPs, while subjects perform complex control tasks.

c. Begin an experimental program designed to determine if ERP components such as N190, P300 or the CNV behave in the operational environment in the same manner they behave in the simpler lab situations. This, for example, will include the following experiments.

   c.1 Determine the utility of N190 ERP component as a measure of reserve capacity, by recording N190 to irrelevant but rare stimuli at carefully controlled levels of task difficulty.

   c.2 Determine the utility of P300 as a tool in evaluating the scope and content of the focus of attention, by presenting subjects with a very complex display, different elements of which may be relevant to the subject's task at any time.

   c.3 Determine if any ERP component can be used to communicate to complex display system which of many possible displays a subject requires to optimize task performance.

d. Develop in the Aviation Research Laboratory a capability for recording ERPs from subjects operating the GAT cockpit simulator. During the first year this will require the installation of physiological recording equipment. By the third year, however, a full scale computerized data acquisition system will be developed at ARL.

2.2 The development of a CAI environment for ERP testing.

The use of ERP components in man machine communication is feasible only when computer power is available in the system. The student-console interaction which characterizes computer assisted instruction is therefore a natural candidate environment for our tests. As in the performance-enhancement task individuals must exchange information with a computing system. The goal here, of course, is to modify the information store of the operator rather than to provide "efficient" control of the console. Yet, the transactions between the student and his "teacher" need to be so designed that the computer's resources are utilized optimally to enhance the student's understanding and retention of the material. In this context it is conceivable that valuable information about the student's interaction with the computer can be obtained through the use of ERP components. With ERPs the "Instructor" might seek to find out how surprised was the student when an answer he gave turned out to be correct (or incorrect). How helpful was the additional information just supplied in reducing the student's uncertainty about his choices? How ready is the student to respond?

The use of ERPs in the CAI environment is somewhat less straightforward than their use in the performance enhancement area, where performance enhancement can be rigorously defined and measured. The tangible effects of instructional improvements are always difficult to describe and to measure. In fact, it might very well be the case that ERPs will contribute to this field through the provision of such criteria.

To fully implement a research program into use of ERPs in the CAI environment it will be necessary to develop a laboratory in which the PLATO terminal has capabilities not normally available in the standard PLATO terminal. The "intelligent" terminal should allow for large scale exchange of data, and synchronizing signals, between our laboratory computer and the

PLATO system. Moreover, we should have faster and more sophisticated graphic capabilities within the PLATO lessons to allow fine control of the stimulus parameters used in invoking the ERPs. We also anticipate a need for interchange of data between PLATO, our lab system and the ARPANET. All of the above capabilities are provided by the Intelligent PLATO Terminal developed under the direction of Professor Roger Johnson of Computer Assisted Education Research Laboratory at the University of Illinois. One of the prime tasks therefore, during the first project period, would be the installation of the PDP/11 based PLATO terminals and its interfacing to a physiological recording system. As soon as possible we will begin to develop techniques for measuring ERPs associated with specific events in the PLATO lesson. Thus, for example, we shall try to record ERPs elicited by the "arrow" (response solicitor) in the PLATO frame, or by the "OK" vs "error" indicators following a student's response. Cortical activity preceding the "NEXT" button press. We are currently arranging to install a standard PLATO terminal in our laboratory. Immediately upon its installation we will begin developing a repertoire of CAI-ERP procedures on which basis a detailed experimental program could be developed.

During the first year we shall identify classes of events in a CAI lesson stream which are reliably associated with ERPs. Several specific experiments will be carried out to assess the meaning of the ERP vocabulary in a CAI context. In parallel, we will install the advanced PDP/11 based PLATO terminal. By the time it is operational the preliminary testing with the standard terminal will be completed and a full scale program would be underway.

2.3 Methodology: Single trial extraction techniques.

Using data currently on hand, as well as data collected during the project period, we shall continue our development of STSE procedures. The

following illustrates the projects to be undertaken.

a. Evaluate discriminant functions developed on the basis of a single recording site. This work is on-going. The functions we have are quite powerful. We will continue to validate the available functions against behavioral data and we will develop at the same time software required to move as much of the required computation on-line as possible.

b. The single electrode techniques will be extended to incorporate data from several channels (electrodes). This will clearly improve the power of the discriminant function.

c. Use the autoregressive procedure developed in our laboratory by Ron Herning to eliminate the "noise" from the post-event EEG, in an attempt to enhance the power of the discriminant functions.

d. Continue to test various non-linear and clustering algorithms as alternates to linear discriminant analysis.

e. Continue the development of factor-analytic techniques in the dissociation of ERP components. In particular, focus on procedures that would allow the use of factor-scores of single trials in on-line discrimination.

f. Considerable emphasis will be placed on the development of cross-subject discriminant functions. Alternately, we will search for techniques which will allow the adjustment of general functions to data from individual subjects. The scenario we have in mind is one in which a universal function is developed off-line, yet for each subject a brief "calibrating" on-line sequence will allow a full adjustment of the universal function to his idiosyncratic waveforms.

Successful, and cost effective, implementation of this plan is contingent on the availability of a system that would allow the management, and ready processing, of rather large data bases. We need a combination of local computing power, a sophisticated data management facility and efficient, reliable, access to remote number-crunching machines. The PDP11/70 will provide all of this in addition to its role as the central node in the network of laboratory computers that will control the experiments and manage the data acquisition.

2.4 ERP vocabulary identification.

This activity stream is a direct continuation of work currently conducted in our lab with ARPA support. Many experiments are planned. The following can serve as illustration.

a. Does P300 depend on the feedback qualities of the eliciting stimuli? Subjects perform a "motor" task and are informed of their success or failure. It turns out the P300 amplitude for the ERP elicited by the correct indicator depends on the difference in intensity between the "correct" and the "error" indicator. The precise conditions under which this interaction occurs must be determined.

b. Data we are collecting now suggests that the amplitude of P300 depends on the rate at which the stimuli occur. A parametric study of this effect is clearly called for.

c. The "novelty" component, (N190), must be studied in great detail. While the present data suggest that it is enhanced in EPs elicited by rare, irrelevant stimuli, these conclusions must be tested in other circumstances.

d. The relation between the Readiness Potential and the CNV must be cleared up if we are to be able to infer with precision the subjects'

"intentions" from anticipatory waves. We believe that the CNV represents a general preparatory process which is maximal over the area of the brain which needs to be prepared for a given task. Tests of the laterality of the CNV under conditions of motor and cognitive preparation will be conducted.

e. If the CNV represents, as many believe, a preparatory process generated in the brain's attempt to optimize performance, then there ought to be a high (negative) correlation between CNV amplitude and reaction time. The literature suggests that this is not the case. We feel that the present literature did not do justice to the problem because it treated the Reaction Time as a uniform variable. Reaction time in fact is determined by a variety of stimulus intake, information processing, and response selection processes. We plan a series of studies that will dissociate Reaction time into its constituents and determine to which of these constituents ERP components relate. This will present a major, and novel, deepening of our understanding of the ERP vocabulary.

f. We are now studying the degree to which P300 amplitude reflects the salience of elements of a compound stimulus. We discovered that visual and auditory P300 can be clearly discriminated and that their relative amplitude seems to reflect the salience of the modality. We plan to extend our investigations of this rather powerful procedure.

g. The recent development of a relatively inexpensive speech synthesizer - the Votrax - which can drive our PDP/11 to generate precisely defined verbal stimuli makes it feasible to broaden the dimensions of stimulus materials we use in P300 studies. We

plan to acquire a Votrax and use it to determine if P300 can be elicited by "unexpected" stimuli, when the oddity of the stimuli is controlled through varying semantic and linguistic dimensions.

This is but a small sample of the experiments which we would like to run as part of activity stream C. Needless to say these studies will provide data for testing and developing STSE techniques as well as provide models for the experiments conducted in the performance and CAI setting.

3. Facilities Available

This project will be conducted in the Evoked Potential Laboratory (EPL) in the Department of Psychology as well as in the Aviation Research Laboratory. The EPL currently occupies 1182 ft^2 of laboratory space, (exclusive of office space allocated to our use). The Department of Psychology is ready to commit this space for our use for the duration of the project. The Department has also recognized that the full complement of laboratories and facilities called for in this proposal will require the commitment of substantial additional space. It is a measure of the support we have in the Department that additional space ranging up to 700 ft^2 of laboratory space will be allocated to this project. Office space for project personnel will also be provided in the Psychology Building.

While the Psychology Building is a splendid structure, built in 1968, and is exceptionally well designed to support a large, research oriented, department, the specific needs of this project will call for several, substantial, renovations. All will be in support of the multiple computer environment we are planning. Specifically the need will arise for (a) installing sufficient electrical power to support the computers, (b) installing a raised floor in the room that will house the PDP11/70 and the PDP11/40 and (c) providing additional airconditioning and humidity control for the

computer room. Estimating the precise cost of these renovations requires engineering effort. Gross estimates made by our Physical Plant engineers are that the total cost will probably be in the neighborhood of $50,000. The University has undertaken to introduce the required changes, and to charge no more than $50,000. The University will cover all cost over-runs which exceed this estimate. If the renovations are less costly, the allocated funds will remain in the contract for use as directed by ARPA, or applied against other expenses.

The Aviation Research Laboratory, Institute of Aviation, University of Illinois offer unique facilities to support aviation research in the areas of systems design, personnel selection and training. The Institute has a fleet of approximately 40 training aircraft and 6 training simulators. The Laboratory facilities include a Specialized Flight Simulation Facility consisting of a Singer-Link GAT-2 simulator and a Raytheon model 704 digital computer, a Digital Equipment Corporation model PDP11/40 digital computer and a terminal on PLATO IV, the University's CAI system.

The GAT-2 simulator consists of a self contained computer, two place cockpit and a two axis motion system. Its motion system, flight controls and instrument panel have been extensively modified to satisfy requirements of the research programs. An external visual display for presentation of computer generated graphics by means of a television data link is currently being installed. In addition, it has been interfaced to the Raytheon 704 digital computer for auxillary computations and automated data collection.

The two computers are connected by means of a high speed interface. Each computer includes a compliment of peripheral devices as well as signal conversion equipment and a DIGIVUE plasma panel with a touch input feature. Specialized hardware for alpha-numeric symbol generations, random number generation, matrix multiplication and computer generated speech is also

included. The PDP11/40 is connected by means of a telephone line to the DEC 10 located in the Coordinated Sciences Laboratory.

During the first two years of the project the bulk of the activity will be at the EPL. However, we are planning to begin recording ERPs within the simulated cockpit's of ARL within the third year of the project. The budgetary implications of this plan will be described below.

FOOTNOTES

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Donchin, E., Kubovy, M., Kutas, M., Johnson, R. Jr., and Herning, R. Graded changes in evoked response (P300) amplitude as a function of cognitive activity. Perception and Psychophysics, 1973, 14: 319-324.

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(4) Donchin, E. A multivariate approach to the analysis of average evoked potentials. IEEE Transactions, Bio-medical Engineering, 1966, BME-13: 131-139.

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ANNOTATED LIST OF PUBLICATIONS OF RESEARCH SUPPORTED BY ARPA

A. *General Reviews*

A.1 Donchin, E. Brain electrical correlates of pattern recognition. In Signal Analysis and Pattern Recognition in Biomedical Engineering, (Inbar, G., Ed.). John Wiley, 1975, 199-218.

This overview of our approach to the study of ERPs as an indicant of cognitive activity was presented, by invitation, before an International Symposium on Signal Analysis and Pattern Recognition held in Haifa, Israel in 1973. It was intended for an audience of non-specialists and it therefore presents a general introduction to evoked potentials in general as well as to the work of this laboratory.

A.2 Donchin, E. (Ed.) The relationship between P300 and the CNV. A correspondence and an experimental report. In Event Related Slow Potentials of the Brain (McCallum, C. and Knott, J., Eds.) Proceedings of the 3rd International Congress on CNV and Slow Potentials, Bristol, England, August 1973 (in press).

A detailed discussion of the relation between the CNV and P300. This report bears directly on the elucidation of the ERP vocabulary. It is in fact the edited transcript of a mail correspondence workshop held during 1973. It illustrates the conceptual and methodological problems that are encountered in an attempt to deal with vocabulary problems.

A.3 Donchin, E. (Ed.) Publication criteria for studies of evoked potentials (EP). Report of the Methodology Committee. In Proceedings of the International Symposium on Cerebral Evoked Potentials in Man (Desmedt, J., Ed.) Brussels, April 1974 (in press).

The report on an international committee organized and chaired by E. Donchin on the proper procedures to be used in ERP research.

A.4 Donchin, E. and Heffley, E. Using minicomputers in the signal averaging laboratory. American Psychologist, 1975, 30: 299-312.

A description of the laboratory developed with ARPA's support. A detailed discussion of the hardware and software required for the successful implementation of ERP research is included.

B. Measurement Problems - The STSE Technique

B.1 Donchin, E. Measurement problems in slow potential research (Opening remarks). In Event Related Slow Potentials of the Brain (McCallum, C and Knott, J., Eds.) Proceedings of the 3rd International Congress on CNV and Slow Potentials, Bristol, England, August 1973, in press.

A brief review of the application of discriminant analysis to ERP data.

B.2 Donchin, E. and Herning, R. I. A simulation study of the efficacy of stepwise discriminant analysis in the detection and comparison of event related potentials. Electroencephalography and Clinical Neurophysiology, 1974, 38: 51-68.

A detailed analysis of the efficacy of stepwise discriminant analysis when applied to ERP data. The final section of this paper presents a demonstration of the approach we plan to use in the on-line detection of "single-trial" cognitive events.

B.3 Herning, R. I. and Donchin, E. The use of ERPs in the assessment of sensory sensitivity. (in preparation)

This report, now in the final writing stages, describes an extensive test of the procedures outlined in the final section of Donchin and Herning (B.2) using auditory evoked responses. The same data base has been used for Herning's dissertation study on the application of autoregressive techniques to single trial detection.

B.4 Squires, K. and Donchin, E. *Beyond averaging: The use of discriminant functions to recognize event related potentials elicited by single auditory stimuli.* Electroencephalography and Clinical Neurophysiology, 1976 (in press).

A demonstration of the efficacy of stepwise discriminant analysis in the detection of the P300 component of the ERP.

C. Studies Related to the Readiness Potential

C.1 Kutas, M. and Donchin, E. Studies of squeezing: The effects of handedness, the responding hand, and response force on the contralateral dominance of the readiness potential. Science, 1974, 186(4163): 545-548.

A preliminary report on the relationship between the responding hand, handedness and premotor negative waves. Study was important in demonstrating the need for analyzing the multiple behavioral determinants of ERP components.

C.2 Kutas, M. and Donchin, E. The effect of handedness, the responding hand, and response force on the contralateral dominance of the "readiness" potential. In Proceedings of the International Symposium on Cerebral Evoked Potentials in Man (Desmedt, J., Ed.) Brussels, April, 1974 (in press).

A very detailed report of the study reported in Kutas and Donchin (C.1).

C.3 Kutas, M., McCarthy, G., and Donchin, E. Differences between sinistrals' and dextrals' ability to infer a whole from its parts: A failure to replicate. Neuropsychologia, 1975, 13: 455-464.

An analysis of various handedness tests undertaken as a preliminary to further elucidation of the relation between the hand in use and handedness.

C.4 Donchin, E., Kutas, M., and McCarthy, G. Comparison of the hemispheric asymmetries of the "Readiness Potential" and the "CNV." Paper read before the Psychonomic Society 15th Annual Meeting, Boston, Massachusetts, November, 1974.

A detailed publication based on the study reported in this brief meeting presentation is now in writing. The study suggests that the scalp distribution of negative "expectancy" waves varies with the specific nature of the expectancy.

C.5 Donchin, E., Kutas, M., and McCarthy, G. Electrocortical indices of hemispheric utilization. In Lateralization in the Nervous System (Harnad, S., Ed.) New York, Academic Press, in press.

A review of the literature, a methodological critique of the literature and a report of several of our own studies.

D. Studies in the ERP Vocabulary

D.1 Donchin, E., Johnson, R., Herning, R. I., and Kutas, M. Covariation of the magnitude of the CNV and P300 as a function of the subject's task. In Event Related Slow Potentials of the Brain (McCallum, C. and Knott, J., Eds.) Proceedings of the 3rd International Congress on CNV and Slow Potentials, Bristol, England, August 1973, in press.

A demonstration that P300 is not a dichotomous phenomenon, but rather varies as a function of subject task. Preliminary data presented on the differential scalp distributions of the CNV and P300.

D.2 Donchin, E., Tueting, P., Ritter, W., Kutas, M., and Heffley, E. On the independence of the CNV and the P300 components of the human averaged evoked potential. Electroencephalography and Clinical Neurophysiology, 1975, 38: 449-461.

This study, which follows up on Donchin et al.'s discussion (A.2) has definitively demonstrated that the CNV and P300 are independently controlled ERP components, and that P300 is independent of prior expectancies. This paper also describes in some detail the use we make of a combination of Principal Component Analysis and Analysis of Variance in measuring ERP components.

D.3 Squires, K. C., Donchin, E., Herning, R. I., and McCarthy, G. On the influence of task relevance and stimulus probability on ERP components. Electroencephalography and Clinical Neurophysiology, in press.

This study demonstrates the existence of multiple endogenous components in the 190 - 500 ms latency range. The paper is important in that it delineates the variables affecting P300 as well as reporting the discovery of N190, a component apparently related to "novelty" (?) independently of the subject's task.

Copies of the above manuscripts can be obtained by writing E. Donchin, Department of Psychology, University of Illinois, Champaign, Illinois 61820.

EXPERIMENTAL PLANS DEVELOPED AS A RESULT OF THIS PROJECT

1. Human Performance Studies

The attempt to develop a system for the enhancement of human performance through man-machine interaction via an ERP link will proceed along several separate but not independent lines. Because of the potential richness of the information available in the form of separable components within the ERP, more than one aspect of the subject's state may be assessed from each stimulus presentation or from a comparison of the ERPs presented in several modalities within the same period of time. Thus it may be possible, within a task, to monitor overall level of performance, the relative division of attention among sets of stimuli, and the amount of information or utilization of information within an attended channel.

The end product of the research will be a system which utilizes all of the information available from the ERP. Initial experiments will, of necessity, be directed at specific aspects of the ERP and what they reflect.

The major emphasis in ERP research has been on components which are associated with the processing of signal information by a subject, thus requiring that signals be relevant to a required task. In such a situation a P300 component is commonly reported. When signals are irrelevant to the subject (for example, when repetitive identical stimuli are presented with no task requirement), the P300 is absent and a simple negative-positive (N100-P200) wave is seen. We have found that under some circumstances an additional component (N190) is also present in the waveforms of ERPs elicited by unattended stimuli (Squires, Donchin, Herning, and McCarthy, submitted for publication). This occurs when a "rare" stimulus is inserted in a regular train of stimuli, even when those rare stimuli have no apparent relevance. Certainly, no overt notice is taken by the subjects of the

stimuli. Thus we infer that at some level of the processing of the signal input the stimulus change has been noted, and reflected in the ERP, but the processing stops at a level prior to that associated with P300 since a P300 component is not elicited.

As N190 has just been discovered a systematic study of its associations is yet to be performed. One plausible hypothesis regarding N190 is that it may index the capability of a person to react to task-irrelevant stimuli while performing in a required primary task. If so, since it requires no activity on the subject's part, the N190 may be a potentially useful tool for assessing the subject's state without interfering with other activities that might be required of the subject.

Investigation of these hypotheses requires the comparison of ERP components while manipulating the amount of processing and response load imposed on the subject. The power of such a comparison is therefore dependent not only on a refined ability to detect ERP events, but also on the existence of appropriate techniques to evaluate performance capacity and task load.

The Aviation Research Laboratory has devoted intensive efforts to develop procedures that will enable the scaling of task levels in terms of operator capacity and task load. These procedures were developed both in focused attention - single task conditions and divided-attention time-sharing situations. Adaptive techniques and elaborated feedback devices are employed to adjust task difficulty and manipulate demands rescaled to correspond with the attention capacity of each subject.

In the first series of experiments ERP will be measured while subjects perform a dual-axis, pursuit, tracking task. The subject will attempt to track a random noise forcing function through a spring-centered dual-axis hand controller. Task difficulty will be manipulated in one of four ways:

(1) *Adaptive change of forcing function frequency (by changing the upper limit of the low pass filter). This represents a stimulus variable.*

(2) *Adaptive change of control dynamic (by changing the relative portions of first and second order determinants). This represents a response variable.*

(3) *Changing the tolerance limits of tracking errors. In this condition all other variables are fixed and performance bar graphs are employed to indicate the instantaneous differences between actual and desired performance.*

(4) *In addition to the above provisions, the program also allows selection of single or dual axis manipulation.*

Subject's performance will be recorded and analyzed on line.

ERPs will be recorded in response to unobtrusive repetitive tone bursts which will be continually present and of no information value within the task. Occasionally one of the tone bursts will be of a different frequency or intensity from the others and will elicit a waveform characterized by an N190 component. Several levels of task involvement will be tested ranging from performing the task at a very easy level up to the maximum level the subject is capable of, along with the appropriate control conditions.

Data analysis will be based on our standard factor analytic procedures which allow an examination of ERP components as a function of the performance capacity required for the primary task. It is expected that N190 might be an index of reserve capacity available for monitoring events outside of the primary task and therefore will vary inversely with the independent task difficulty variable. Likewise, the N100 component may vary in a comparable manner but to a lesser extent, and under some conditions, such as for the

easy task, the P300 compone[illegible] may emerge in the waveform.

Additional work will be directed at single trial determinations of reserve capacity based upon the averaged ERP results and utilizing the single trial waveforms from the experiment. The end product of this first experiment will then be a calibration procedure for using the ERP to unobtrusively monitor subject state.

A complimentary approach will be used to evaluate ERP waveforms elicited by stimuli which are directly relevant to the subject's primary task. On the basis of previous work it can be predicted that certain components, namely N100 and P300, are enhanced when attention is paid to particular stimuli. An additional component labeled the "slow wave" (SW) has also been recently discovered and seems to fall within the class of attention related potentials. That such enhancement effects occur is well documented, however, no systematic attempts have been made to deal with the effect in terms of quantifiable measures of directed attention.

Such measures are included in the time sharing techniques that were developed in the Aviation Research Laboratory and will be incorporated in this experiment. The experiment will follow the basic paradigm of the secondary task technique; however, several conditions of subtask priorities will be investigated. Subtask priorities in this approach are manipulated by changing the feedback indicators.

Two types of data are relevant to this approach, the stimuli upon which task performance is contingent and stimuli which provide feedback to the subject as to his performance. Feedback stimuli suitable for ERP recording can be incorporated in any performance task including the tracking task. For instance, tone bursts of varying frequency can be presented whenever the subject falls below certain minimum performance criterion. By varying the informative value of feedback stimuli through variations in

redundancy, rate of presentation, and clarity of the stimuli simultaneously in several channels or modalities we will evaluate the usefulness of the P300 and other components as indices of focused attention and information content of feedback stimuli.

Similarly we will approach the problem from the standpoint of the task contingent stimuli. Presentations of target conditions, where a target may be a brief signal or change in a signal, are known to elicit P300 components when a target is detected but not when it goes undetected. Also, non-targets which are similar to targets may also elicit P300s. Thus it is possible to probe the subject within the set of task relevant stimuli to monitor his degree and direction of focused attention.

The data sets from these experiments will allow us to compare the efficiencies of assessing subject state by the four approaches, monitoring of the irrelevant probe ERPs, relevant feedback ERPs, relevant task stimulus ERPs, and irrelevant probe stimulus ERPs within a relevant channel.

2. ERPs in the CAI Laboratory

Though the application of ERP techniques to a CAI environment is largely an unexplored area the implementation of such a program is expected to yield mutual benefits. The PLATO lesson provides an environment within which highly relevant, verbal material is presented to a subject who processed the information, makes a decision, makes a response and then receives feedback regarding that response. The PLATO "instructor" presently has access to the subject's behavior only through his response on the touch panel or keyboard. Since one of the main thrusts of ERP research has been to isolate certain ERP correlates of information processing and decision making it may now be possible to supplement the instructor's knowledge about the student by providing measures of ERP activity during the question-

answer-feedback sequence. In the (distant) future it may be possible to eliminate the behavioral response altogether and rely entirely upon ERP to direct the course of a teaching session.

For example, in addition to the subject's behavioral response the instructor-computer can monitor the ERP elicited by the feedback signal on each trial. It has previously been shown (by members of this laboratory) that the amplitude and latency of the P300 component following a simple visual feedback signal vary as a function of whether that signal confirms that the response was correct or indicates that an error was made. Furthermore, these measures vary according to the confidence with which the original decision was made. When a subject is highly certain of his decision and is informed that the answer was correct, a small, early P300 component is elicited. However when told that an equally certain answer was wrong the ERP shows a much larger and somewhat later P300 component. When the subject is uncertain of his decision, P300 components of intermediate amplitude and latency are found. Thus, the feedback ERP potentially provides a continuous scale along which the subjects' decisions on each trial can be assessed by the instructor computer to determine the current level of understanding within the lesson.

The above results apply to simple feedback signals, the flash of a colored light or a tone burst of a particular frequency, in psychophysical detection and discrimination tasks. We must determine if these results will transfer to a situation wherein linguistic messages are presented visually within a realistic learning task.

A simple learning task will be developed or taken from available PLATO lessons. The lesson will be selected so that it presents material which is novel to the subject population and yields responses which span a wide range of certainty on the part of the subject. Confidence-rating responses

will be collected to directly assess the certainty in each decision and average ERPs will be collected according to the combination of confidence rating of the decision and valence of the feedback (confirming or disconfirming). Additional control conditions will also be presented within which non-informative "feedback" is presented and waveforms to such stimuli also collected.

This initial experiment will be presented visually and utilize as much of the standard PLATO protocol as possible but will be idealized to the extent that all known potential artifacts and problems that may occur in a more realistic situation are eliminated. This will entail fixed record lengths, fixed location of feedback presentation, fixed inter-trial interval, etc. Loosening of such contraints will be incorporated in subsequent experiments when the effects of each presentation variable are worked out.

Data analysis will consist of a detailed analysis of the ERP waveforms which is standard in our laboratory. This includes a factor analysis to isolate components of the complex ERP waveform. The resulting components will be assessed as to their relationship to the independent variables (stimulus "OK" and stimulus "ERROR") and dependent variables (certainty and stimulus valence) and compared with analogous components from feedback in a simple detection task. Of special interest are variations in component amplitude over the surface of the scalp which will be determined through the use of multiple (10-12) channels and which have not been adequately measured up until now. Particular emphasis will be placed on determining which aspects of the ERP waveform are most powerful in segregating the waveform types and which aspects are common to all information processing tasks. Data collected here will be incorporated into the expanding data base we have from a number of separate tasks.

Further experiments will deal in greater depth with other aspects of

the question-response-feedback sequence. For instance, it is expected that the pre-feedback CNV may index decision certainty and feedback expectancy in a manner complementary to the feedback ERP. Likewise there is an expected link between the subject's decision and the time of occurrence of his behavioral response.

Other variables which should be studied are the information content of the feedback stimulus (i.e., right-wrong versus the correct answer, which then must be interpreted to determine the valence, and vice-versa), the response feedback delay, spatial position of the feedback, the relative contrast of feedback versus the array already on the screen, and many other technical and procedural points.

It is expected that Experiment I can be completed within the bounds of our current expertise, given that the required equipment is available, and should lead to many more sophisticated experiments which will be outlined later.

3. Further Developments of ERP Vocabulary

The vocabulary of the ERP as we now know it includes a pre-signal component (CNV), a pre-activity component (readiness potential), two signal related components (N100, P200) and at least three post-signal components related to the processing of significant events (N190, P350, and SW). While all are robust phenomena and their occurrence can often be predicted, it can be safely stated that neither the anatomical nor psychological bases of any of these components is fully understood. In addition, the improved resolving power of the techniques of ERP recording and analysis promise to continue providing new ERP phenomena. The N190 and SW components, for instance, which were first described within the past year, went unnoticed until multi-channel recording was used and subsequent factor analysis

techniques applied to the data to isolate the otherwise temporally entangled components. Thus an important facet of this work effort will be the continuation of study programs targeted at a complete psychological description of the existing vocabulary and identification and isolation of new ERP components.

A description of the N190 component in a performance setting and efficient evaluation of it as a biocybernetic tool must be supported by an improved understanding of the basic parameters governing its behavior. Anecdotal evidence suggests that N190 is more pronounced when rare low intensity stimuli are introduced into a train of higher intensity tone bursts. In some other cases it appears that frequency shifts elicit clearer N190s than do intensity shifts. Clearly it is important to determine the optimum conditions for eliciting N190, thus increasing the signal-to-noise ratio, if it is to be used efficiently to monitor variations in the state of a performing subject, particularly on a single trial basis. To do this a parametric study will be performed wherein stimulus and timing variables such as frequency, intensity, direction, and amount of intensity or frequency change for auditory signals; rate or stimulus presentation and density of rare stimuli; and modality of presentation, auditory, visual, and somesthetic.

An unexpected result from a recent study conducted in our laboratory is that the N190 component in an auditory intensity shift experiment is apparently lateralized to the right hemisphere and largest over the frontal cortex. Post-hoc explanations of such a result can be made from the literature on cerebral dominance, however such a finding clearly merits systematic study before conclusions are reached. Several possibilities exist, such as that N190 may be modality specific and distributed differently for, say, auditory and visual stimuli; it may be task-related and

vary according to the design of the primary task, for instance, manual versus linguistic; or it may be a function of the level of significance and pattern of the secondary stimuli, as in a linguistic versus a musical pattern. These and other hypotheses will be examined in conjunction with experiments conducted in the Performance and CAI studies.

One hypothesis regarding the relationship between P300 and cognitive events is that P300 reflects post-stimulus processing of feedback information provided by a signal which modifies expectancies of receiving subsequent signals or modifies subsequent responses. As such the P300 component will depend upon the quality of the feedback information as well as its usefulness in determining subsequent behavior. In a current study we have found that auditory feedback stimuli indicating the success or failure of preceding motor performance elicit different amplitude P300 components according to the intensity relationship between "correct" and "incorrect" stimuli. Since all stimulus pairings are readily distinguishable at the level of a psychophysical discrimination and are presented within series which are identical from the aspect of motor task performance, an additional factor is evidently present which modifies the effectiveness of the feedback information in eliciting P300. We plan to investigate this phenomenon by first determining the critical parameters of stimuluation which cause such an effect, such as variations in the response-feedback interval, and then determining the level at which the stimulus information is modified, for instance, does the discrimination take longer for some stimulus pairs even though the final decision (as measured by the discriminability) is the same for all pairs.

In another ongoing experiment we have found that the P300 component elicited by rare target signal within a train of non targets varies widely in amplitude according to the rate at which stimuli occur and according to

the randomness of the inter-stimulus interval. Prior to establishing any general predictive hypothesis regarding P300, the relative importance of each of these experimental variables and any possible interactions must be determined. We plan to conduct a thorough parametric study of this effect.

Prior to expected signals which initiate motor operations and cognitive events, two ERP waves have been described, the readiness potential and the CNV. The relationship between the two ERP components and the relevant behavioral variables are as yet not clear. In fact it has not been established whether they represent differing brain processes, one unique to motor tasks and one to cognitive events or whether the components reflect a general preparatory process common to both types of task but localized to the particular areas of the brain involved most heavily in each task. It will truly enhance the understanding of brain-behavior relationships if we could determine which brain regions are involved in given behavioral tasks by assessing the degree to which they are "readied" in anticipation of processing. Our approach to the task will be to map the scalp distributions of CNVs when subjects engage in different behaviors designed to shift the locus of major areas of brain involvement. Careful analysis of asymmetric scalp distributions and time courses of the CNV across and within tasks should aid in the determination of the basis of the CNV.

A question that merits careful consideration is that of the relation between CNV-like potentials and Reaction Time. The low correlations between CNV amplitude and reaction time when measured on a trial by trial basis are quite difficult to interpret within the context of accepted accounts of the CNV. If the CNV represents a cortical attempt to optimize performance then one would expect a correlation between optimal performance and the CNV.

There are at least two possible explanations of the low correlations reported in the literature, each leading to an important series of experiments.

First we note that the Reaction Time is a multiply determined interval representing the total duration of serial, and parallel, stages in the stimulus reception-response execution sequence. Among such stages are stimulus reception, stimulus recognition, response selection, and response execution. The CNV may well reflect processes germane to one such stage and not to the others. We plan a series of studies in which Reaction Time variance would be partitioned into its constituents and each constituent will be separately related to the CNV. This will. of course, provide a finely tuned analysis of the behavioral significance of the CNV.

An alternate explanation for the weakness of the CNV/RT relationship is that CNV amplitude varies between trials as a function of, say, subject's reserve capacity, in order to maintain a constant, optimal, RT. If this is the case the correlation between CNV and RT will indeed be small, even though there is a strong causal relationship between the CNV and RT. This hypothesis can be tested in a setting which permits measures of "reserve capacity" while the CNV and RT are determined. This setting will be provided in the laboratory setting we are developing.

The recently described SW component is, because of its slow time course, possibly related to other slow potential changes such as the CNV. In some paradigms the presignal CNV can be seen to "resolve", or return to an equipotential condition, following a stimulus presentation, causing what appears to be a positive wave if only post-signal events are analyzed. The SW may be such a phenomenon. If so, it would be the offset of a very unique CNV because of its inferred distribution, which would differ from previously described CNVs, and, because no phasic CNVs occur between stimuli the phenomenon would have to be a tonic CNV, something that has not yet been reported. We are planning to investigate this question using multi-channel D.C. recordings and a procedure to pick up both the SW component and the onset of any tonic CNV.